Mastering Phase Noise Measurements (Part 1)

Application Note

Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise.

Note: This application is part one of a three part series. See the end of this application note to view the other two parts.

Rohde & Schwarz
10.2016 – 01.01

ROHDE&SCHWARZ

Table of Contents

1 Introduction 3

2 Understanding the Basics 4

2.1 What is Phase Noise? 4

2.2 Relationship to Jitter 5

2.3 Why is Phase Noise Important? 6

2.3.1 Digital Modulation Systems 6

2.3.2 Communication System Transmitters 6

2.3.3 Receivers 7

2.3.4 Radar 7

2.3.5 Digital Systems 7

2.4 Quantifying Phase Noise 7

2.5 Causes of Oscillator Phase Noise 9

3 Summary 10

2 Introduction

Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications. Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

- **Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise**
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

We will first cover part 1: Understanding the basics of phase noise

3 Understanding the Basics

Let's first make sure that there is a good understanding of what phase noise is and where it comes from.

3.1 What is Phase Noise?

In a perfect world a signal would be an ideal sine wave, mathematically pure. If it were measured on a perfect oscilloscope it would look like a perfect sine wave, on a perfect spectrum analyzer it would look like a spectral line with no width and some amplitude (Figure 2-1a). It would have no phase noise or amplitude noise. This signal would be defined as

$$V(t) = A \sin(2\pi \nu t) \quad (1)$$

where
A = nominal amplitude
ν = nominal frequency

Unfortunately, perfect signals do not exist in the real world. There will always be some amount of noise on the amplitude part of the signal and with the phase or timing of the signal (Figure 2-1b). The effect of this noise is defined as

$$V(t) = [A + E(t)] \sin(2\pi \nu t + \varphi(t)) \quad (2)$$

where
E(t) = amplitude fluctuations
φ(t) = phase fluctuations

Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain. It's equivalent in the time domain is jitter.

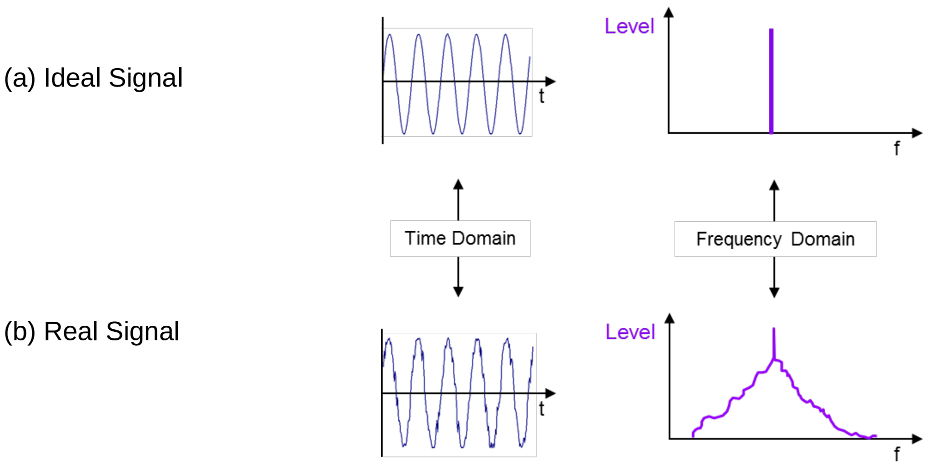


Fig. 2-1: Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain and is equivalent to jitter in the time domain.

Phase noise is typically measured on a device that generates signals, basically an oscillator of some kind. This type of phase noise measurement is called absolute phase noise or 1 port phase noise (Figure 2-2a). Here the goal is to determine how much phase noise is actually produced by the device-under-test (DUT). A second fairly common measurement is additive phase noise. Often when adding a 2-port device, such as an amplifier or an up/down converter, there is interest to know how much phase noise that device adds to the signal (Figure 2-2b).

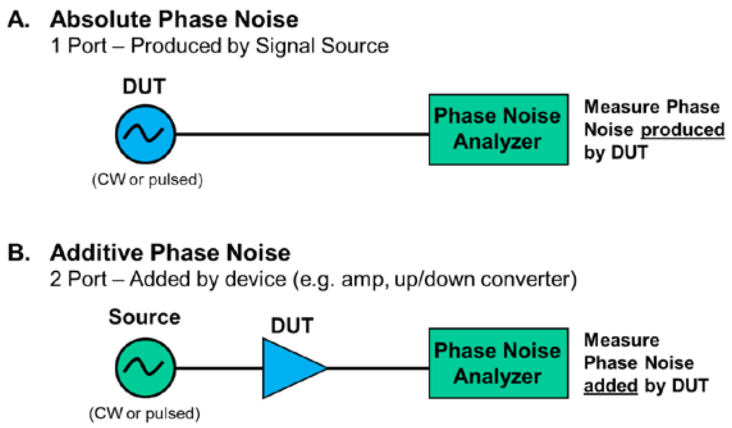


Fig. 2-2: Types of phase noise

3.2 Relationship to Jitter

Phase noise is a frequency domain phenomenon and its equivalent in the time domain is jitter. Jitter has historically been measured with an oscilloscope, which measures in the time domain. Oscilloscopes measure jitter directly and are very flexible in measuring time interval errors, period jitter, and offer different ways of expressing jitter (Figure 2-3).

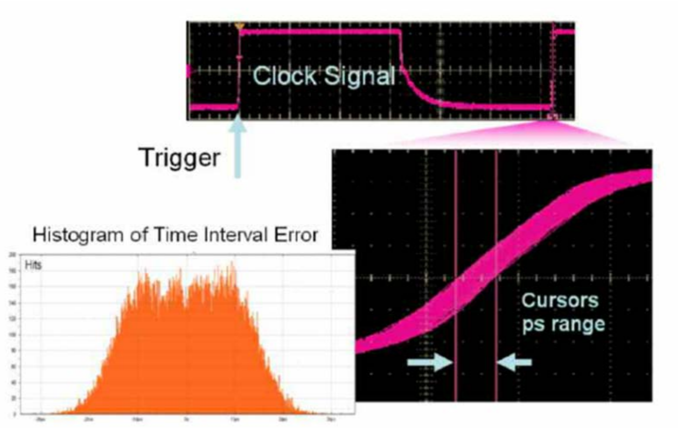


Fig. 2-3: Jitter is a time domain approach to phase noise.

There are two limitations with this time domain technique: sensitivity and cost. Oscilloscopes have a jitter floor they can't measure below, which is typically in the range of picoseconds for general scopes. There are very high-end oscilloscopes that can measure down to 100 femtoseconds of jitter. They can be very expensive, hundreds of thousands of dollars. Due to their high cost access is often limited if at all.

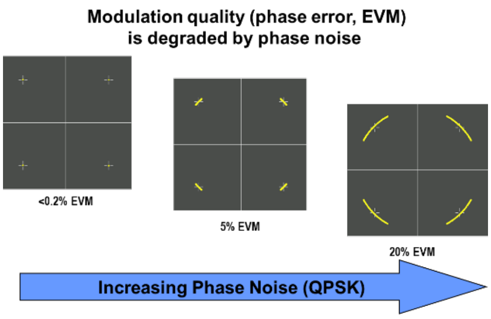
Fortunately, phase noise techniques can measure jitter with excellent sensitivity. Jitter measurements well below 10 femtoseconds (1 fs = 10-15 s) are possible, which is much more sensitive than a typical oscilloscope. To get this level of sensitivity the cost of a phase noise analyzer is almost two orders of magnitude lower. It is relatively easy to measure jitter under 10 femtoseconds with a phase noise analyzer.

Another advantage is that phase noise plots make it easy to distinguish random and deterministic jitter, which is difficult using an oscilloscope. One limitation of the phase noise analyzer is that it can only look at clocks or data streams that have a regular pattern. It does not work with random data stream.

3.3 Why is Phase Noise Important?

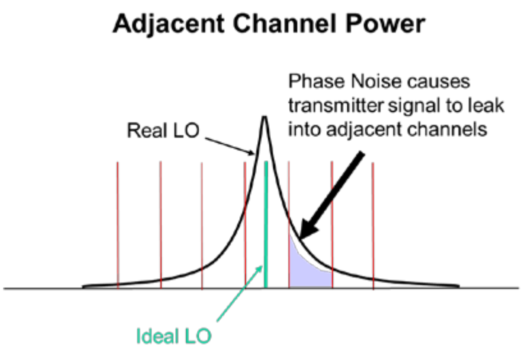
Phase noise matters in a wide variety of applications. It's commonly thought of in terms of modulators and transmitters, but it's also important in receivers. Phase noise can have a significant impact on digital systems, as well as radar systems. The following are a few specific examples.

3.3.1 Digital Modulation Systems



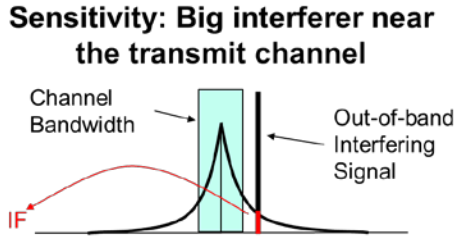
For digital modulation systems, transmitter phase noise can be a limiting factor on modulation quality. Different levels of EVM from increased phase noise will degrade the signal and spread the symbols. In this example a 20% EVM will push the limits of what a QPSK system can handle. This error would be introduced by the transmitter; it is important to recognize that these errors will carry across the channel and the receiver, where there will be further degradation to the signal. Minimizing transmitter phase noise can be critical to a design's success.

3.3.2 Communication System Transmitters



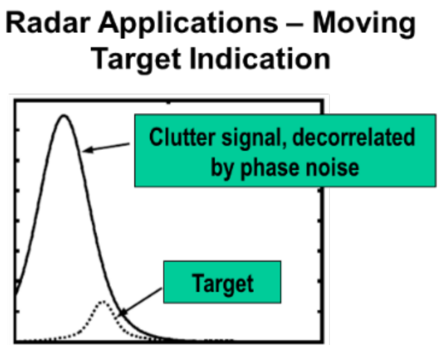
In communication systems, in addition to a transmitter degrading modulation quality, phase noise also spreads the spectrum out. This can result in leakage into adjacent channels. Most communication standards have defined limits on how much signal is allowed to leak into adjacent channels.

3.3.3 Receivers



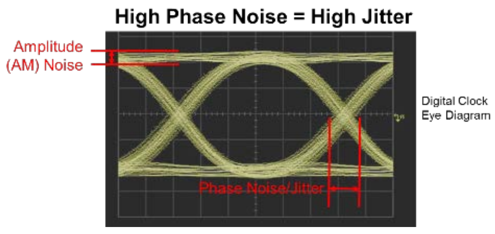
While it is obvious in transmitters, the importance of phase noise is often overlooked in receivers. The phase noise of the local oscillator (LO) inside the receiver needs to be factored into the overall system design. If the phase noise of the LO increases the signal width, even out-of-channel inferring signals can map into the intermediate frequency (IF) and reduce the overall sensitivity of the receiver.

3.3.4 Radar



Radar systems try to receive very faint reflections off of their targets. Often times there may be close-in-clutter that creates a really large reflection. If the width of that reflection is degraded enough by the increased phase noise of the LO inside the radar, it will actually mask the target.

3.3.5 Digital Systems



In the digital world, phase noise is commonly called jitter. It is important to note that jitter is a limiting factor on the quality of an eye diagram. When the jitter gets high, it can cause bit errors and reduce or limit the sustainable data rate. This is becoming increasingly important as the speed of digital systems increase.

3.4 Quantifying Phase Noise

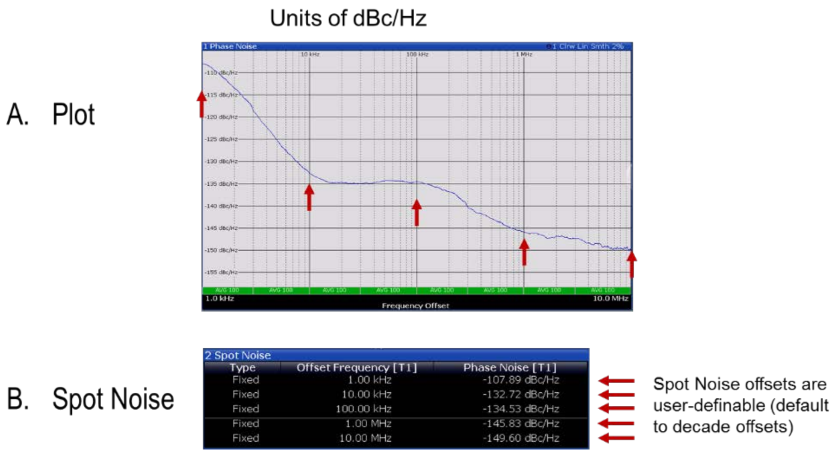
Phase noise is usually expressed as L(f) and is commonly pronounced “script L of f”. A few years ago, the IEEE redefined phase noise to be one-half the spectral density of phase fluctuations, $S\varphi$ (f), or

$$L(f) = \frac{1}{2} S\varphi(f) \quad \text{IEEE STD 1139-2008} \qquad (3)$$

The old definition was defined as single sideband power due to phase fluctuations in a 1Hz bandwidth at a specified offset frequency, f, from the carrier. For users familiar with spectrum analyzer displays this was a bit more intuitive. In both cases it is specified in dBc/Hz.

In many cases it turns out that these two definitions are equivalent for normal, low-phase noise oscillators. The two diverge only when phase noise gets really high and the modulation index gets to where the sideband energy is pushed out into multiples of the sideband frequency.

An example phase noise plot is shown in Figure 2-4a. Typically, a plot goes from a start offset to a stop offset and those offset frequencies are on a log scale. So it's a log-log plot with dBc/Hz on the Y axis and offset frequency on the X axis. A second term, "spot noise," is the same as taking a marker and putting it on that plot to measure how many dBc/Hz are at that specific offset. Most phase noise analyzers provide a spot noise table, where specific offsets can be defined by the user (Figure 2-4b).



Type	Offset Frequency [T1]	Phase Noise [T1]
Fixed	1.00 kHz	-107.89 dBc/Hz
Fixed	10.00 kHz	-132.72 dBc/Hz
Fixed	100.00 kHz	-134.53 dBc/Hz
Fixed	1.00 MHz	-145.83 dBc/Hz
Fixed	10.00 MHz	-149.60 dBc/Hz

Fig. 2-4: Quantifying phase noise.

In addition to measuring the raw phase noise, many times there is interest in what is called "calculated residual noises". The following terms are based off the phase noise curve:

- Integrated Phase Noise $\int \mathcal{L}(f)df$ (dBc)
- Residual PM $\frac{180^\circ}{\pi}\sqrt{2\int \mathcal{L}(f)df}$ (deg or rad)
- Residual FM $\sqrt{2\int f^2 \mathcal{L}(f)df}$ (Hz)
- Jitter $\frac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)df}$ (sec)

Note should be L(f)

3.5 Causes of Oscillator Phase Noise

So what causes phase noise? There are various contributors that, when put together, create the characteristic phase noise curves we are familiar with (Figure 2-5). These contributors are present in varying degrees depending on the type and design of the oscillator:

Random Walk: Close to carrier, generally caused by environmental effects

Flicker FM: Related to active oscillator physical resonance mechanism, power supply noise

White FM: Related to passive resonator oscillators

Flicker φM: Related to noisy amplifiers and multipliers

White φM: Far from carrier, generally caused by broadband output amplifier noise

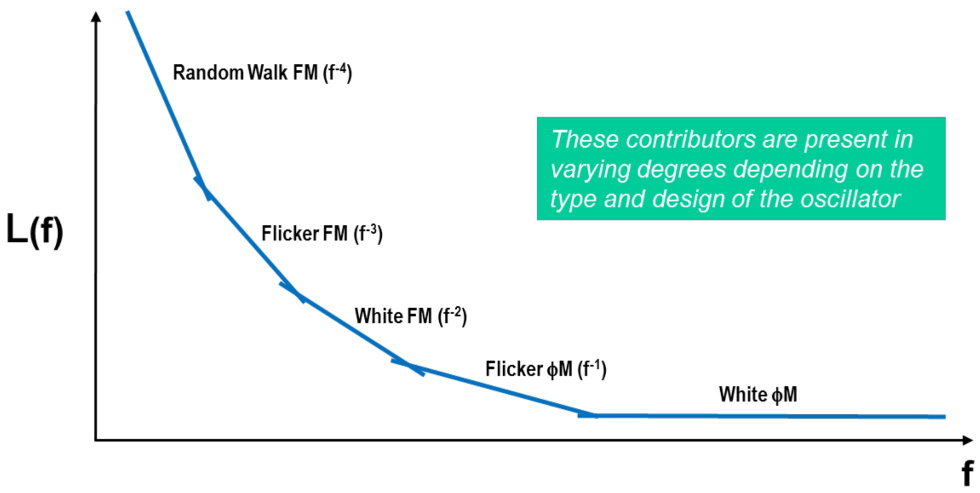


Fig. 2-5: Causes of oscillator phase noise.

4 Summary

Minimizing phase noise is critical to achieving the performance required by many of today's RF applications. This application note Part 1 has provided a basic understanding on the fundamentals of phase noise. We showed how the residual parameters are calculated from raw phase noise data, including the integrated phase noise, residual PM, FM, and jitter.

Part 2 and 3 will look at several traditional measurement techniques and introduce a new technique using the R&S FSWP. While the traditional techniques have been used for years, they are hindered by cumbersome calibration and often require additional hardware. Our new digital phase demodulation technique provides really low-noise reference sources and achieves fast correlations with simple setups that deliver state-of-the-art sensitivity and speed.

Please follow this link for more information on the R&S®FSWP Phase Noise Analyzer and VCO Tester.

- Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management ISO 9001

Certified Environmental Management ISO 14001

This and the supplied programs may only be used subject to the conditions of use set forth in the download area of the Rohde & Schwarz website.

PAD-T-M: 3573.7380.02/02.05/EN/

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com

Mastering Phase Noise Measurements (Part 2)

Application Note

Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique

Note: This application is part two of a three part series. See the end of this application note to view the other two parts.

Rohde & Schwarz
10.2016 – 01.02

ROHDE&SCHWARZ

Table of Contents

1 Introduction 3

2 Phase Noise Measurement Techniques 4

2.1 Direct Spectrum Analyzer 4

2.2 Phase Detector 7

2.3 Phase Detector with Cross-Correlation 9

2.4 Delay Line Discriminator 10

2.5 Digital Phase Demodulator 11

3 Summary 13

2 Introduction

Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications. Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

- Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise
- **Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique**
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

We will now cover part 2: Phase Noise Measurement Techniques

3 Phase Noise Measurement Techniques

Let's review the different measurement techniques that can be used for measuring phase noise. This does not represent all the techniques available, however they are the most common ones used nowadays.

3.1 Direct Spectrum Analyzer

The first and most basic technique uses a spectrum analyzer (Figure 2-1). Spectrum analzers have been used to measure phase noise for decades. It's a simple setup. An oscillator signal can be hooked up directly to the analyzer and a measurement is made.

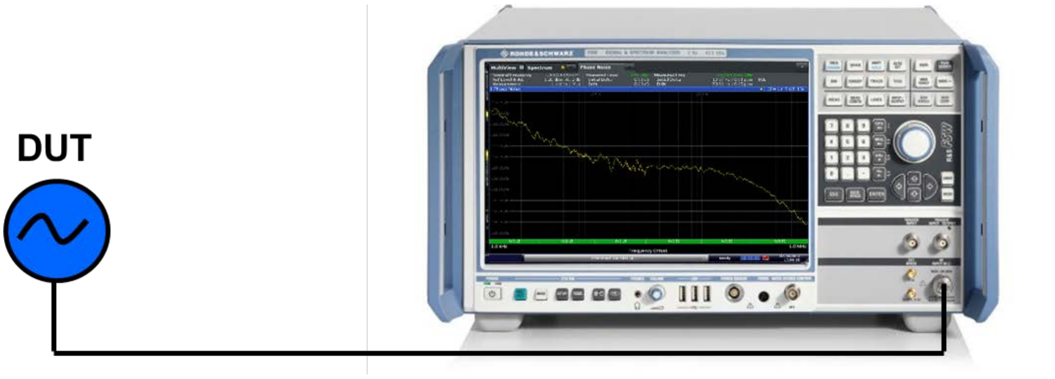


Fig. 2-1; Direct spectrum analyzer measurement setup.

Figure 2-2 shows a generalized block diagram of a modern spectrum analyzer. The incoming signal gets up-converted and down-converted multiple times before it gets to the baseband frequency, where the final signal is analyzed with the DSP hardware. The local oscillator (LO) at each of these stages can contribute phase noise to the overall measurement. For this reason, it is important to make sure that the spectrum analyzer phase noise is lower than the device-under-test (DUT).

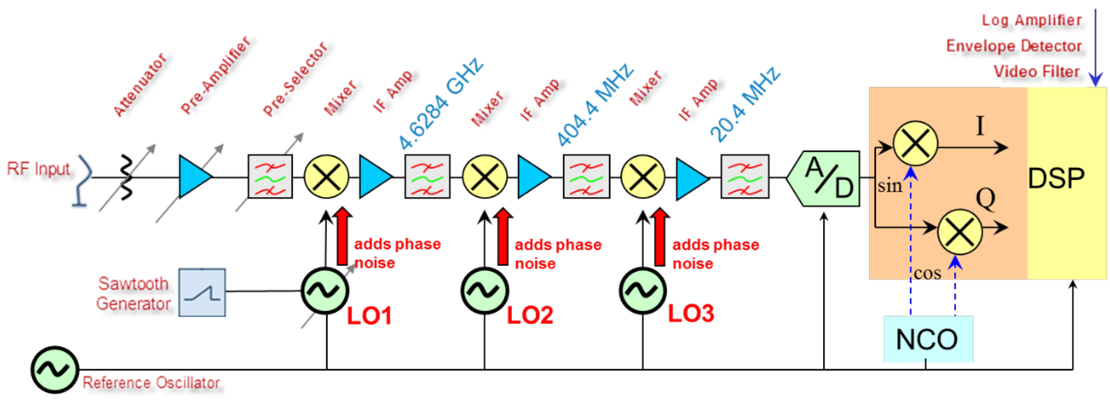
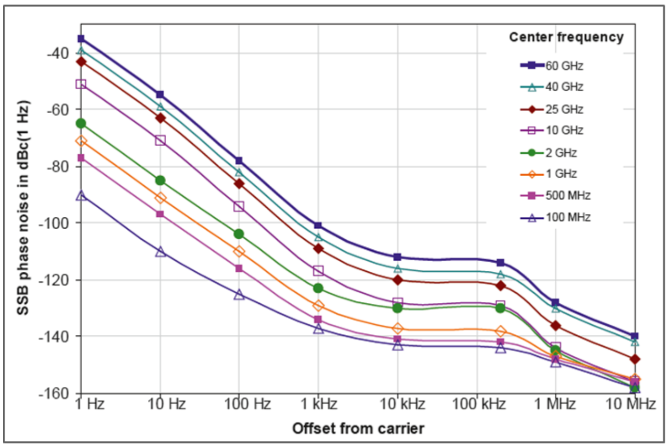


Fig. 2-2: Example direct spectrum analyzer block diagram.

The best way to know if a spectrum analyzer is good enough to make your measurement is to look in the datasheet. Figure 2-3 is a datasheet excerpt for the Rohde & Schwarz FSW spectrum analyzer. It shows, for various carrier frequencies, what the phase noise curves look like at various offsets. The table on the right shows how much measurement error to expect, based on the margin between the spectrum analyzer specification and the DUT's measured phase noise.

For example, if the spectrum analyzer is only 3 dB lower in phase noise than the DUT, the resulting measurement error is going to be +1.8 db. It will always read higher; it never reads lower. So this isn't an uncertainty value, this is bias. It actually adds and throws the measurement off by 1.8 dB in this case.

A general guideline would look to have at least 10 dB of margin between the desired DUT performance and the spectrum analyzer's phase noise. From the table it shows less than a 0.5 dB of measurement error. More is always better as far as margin goes.



R&S FSW Spectrum Analyzer Phase Noise from Data Sheet

$L_{DUT} - L_{SA}$ (dB)	Meas Error (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
10	0.4
15	0.1
20	0.04

Target Margin

Fig. 2-3: Measurement sensitivity is limited by the internal phase noise of the spectrum analyzer.

Spectrum analyzers are usually used in one of two ways: manually or by using a phase noise personality. The manual mode, shown in Figure 2-4, places a marker on the signal peak and moves a second marker at a given offset. Even in manual mode, most spectrum analyzers offer a "phase noise marker", which measures the noise in a given resolution bandwidth and does a correction to normalize to 1 Hz. It also corrects for the Gaussian shaped filters used by the spectrum analyzer, which is called the effective noise bandwidth of the filter.

The manual mode often requires the use of averaging to smooth out the noise. It is important to use power averaging and not log averaging. Years ago, log averaging was the only averaging available on spectrum analyzers, but today modern analyzers will average in the power domain, the voltage domain, the linear domain or the log domain.

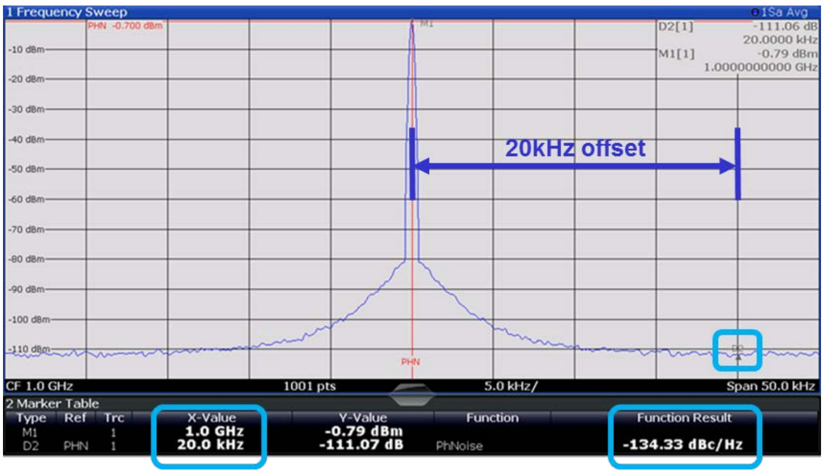


Fig. 2-4: Manual spot noise measurement.

Most spectrum analyzers today offer a phase noise measurement personality, which is typically an add-on option. It takes care of much of the instrument setup and displays the measurement in the typical phase noise format (Figure 2-5). The personality can list spot noise, show a spur list and the residual calculations such as FM, PM, jitter, and so forth.

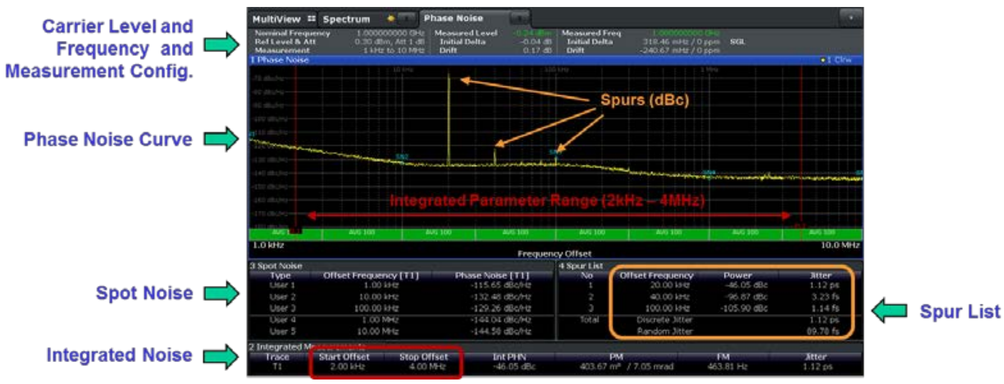


Fig. 2-5: A spectrum analyzer's phase noise measurement personality takes care of much of the instrument setup and displays the measurement in the typical phase noise format.

Spectrum analyzers do have a few limitations. They're scaler instruments, so they generally don't discern the difference between phase noise and AM noise. Normally that's not a problem because AM noise is much lower than the phase noise, especially close in.

Also, even the best spectrum analyzers have only a minimum resolution balance of 1 Hz. Trying to measure close in to a carrier in the neighborhood of 1 Hz or less can't be resolved. Not many applications need to measure that close, but there are some applications where it's important.

In summary, direct spectrum analyzer measurements are fast and easy to setup, especially if using a phase noise personality. Plus, a spectrum analyzer offers something that a dedicated phase noise analyzer may not offer – the ability to measure other things on an oscillator, such as harmonics, adjacent channel power, or spurious and so forth.

A spectrum analyzer is a very versatile instrument, but remember that the sensitivity is limited by the internal phase noise of the spectrum analyzer itself. The datasheet can be used to determine whether it's an issue for you or not.

3.2 Phase Detector

So what happens when the DUT has lower phase noise than your spectrum analyzer? Luckily, the phase detector technique has been around for almost as long as spectrum analyzers. An example block diagram of a phase detector based solution or as they are known, a phase noise analyzer, is shown in Figure 2-6.

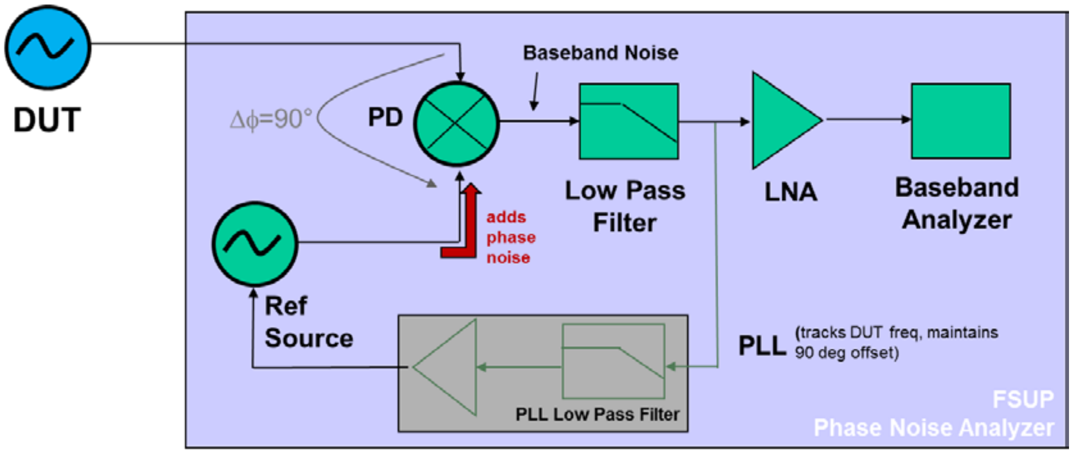


Fig. 2-6: Phase detector block diagram.

The phase detector is basically an RF mixer that has the same frequency going into both inputs. With mixers, the output signal is the sum and difference of the two input frequencies. In this case, where the two frequencies are equal, we get 2x of the frequency and the difference, which is zero or DC.

A benefit of this technique is that the carrier is not present anymore, only low level baseband noise. This reduces the need for high dynamic range. The 2x term is removed with a low pass filter. Adding a high gain, low noise amplifier further improves the sensitivity.

The reference source still adds phase noise, but since it is only a single conversion – not the three or four stages of conversion on a spectrum analyzer. With only one stage, the reference source can be tuned to be very low phase noise.

The phase noise analyzer has a phase lock loop in its design. This keeps the reference source frequency and phase locked to the incoming DUT signal. These two signals are phase locked at 90 degrees out-of-phase. They are kept in quadrature to each other to get the most sensitivity, which occurs right at that 90 degree point.

There is a downside to the phase lock loop. At offset frequencies below the phase lock loop bandwidth, it's also tracking the noise. The loop bandwidth is set as low as possible to still maintain tracking. When trying to make measurements below the loop bandwidth there's going to be some suppression of the DUT noise. Luckily, we know what that suppression characteristic is and can apply an inverse correction to it. A problem occurs when you get more than one to two decades below that loop bandwidth, the correction gets rather large and the uncertainty starts to increase. Try not to make measurements that offset it more than one or two decades below that loop bandwidth value.

Finally, because we no longer need to worry about the minimum resolution bandwidth filter, this technique is able to measure very close offsets since the carrier is no longer present. Down to 0.01 Hz is a typical value on this type of analyzer.

As with the spectrum analyzer technique, it is important to look at the margin between the device under test and the reference source, or the analyzer's inherent phase noise. The table from Figure 2-3 still applies and it is important to have 10 dB margin between the desired DUT performance and the measurement solution, just to keep the error down.

The output of a phase noise analyzer may be formatted differently on the display screen, but it contains all of the same information – spurs, a spot noise table, and residual calculations (Figure 2-7). The key benefit is the better sensitivity and better rejection of AM using this technique.

One final comment on this technique via a phase noise analyzer is that it is a specialized instrument. A key advantage of the spectrum analyzer technique is that it can also measure harmonics, adjacent channel power, digital modulations, etc.

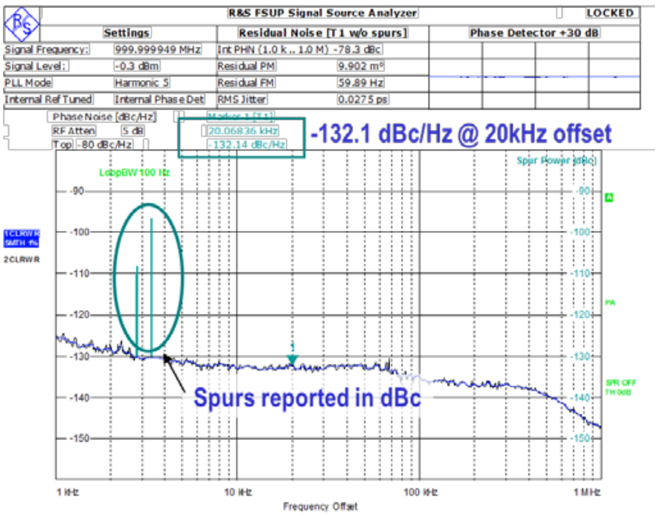


Fig. 2-7: Phase detector display presents results of phase noise, spot noise, integrated calculations, and spur detection (in dBc).

3.3 Phase Detector with Cross-Correlation

What happens if phase detection is still not sensitive enough to measure a super-quiet oscillator? Within the last 15 years or so, a new technique of adding a cross-correlation function has been introduced to improve the sensitivity of the phase detector technique even more.

The cross-correlation technique adds a duplicate set of hardware, a second identical path that includes a different reference oscillator (Figure 2-8). Why is this done? The Reference 1 and Reference 2 oscillators are uncorrelated from each other. By cross-correlating the results of the two measurements over time, the uncorrelated noise from Ref 1 and Ref 2 will tend to diminish, whereas the common noise from the DUT will not diminish. With enough cross-correlation, the measurement effectively reduces the phase noise of the two reference oscillators. If we perform 100 cross-correlations, it results in an effective 10 dB reduction in the reference phase noise. If we perform 10,000 cross-correlations, then it's 20 dB of reduction. This becomes a very sensitive way to make really low phase noise measurements using the phase detector technique with cross-correlation.

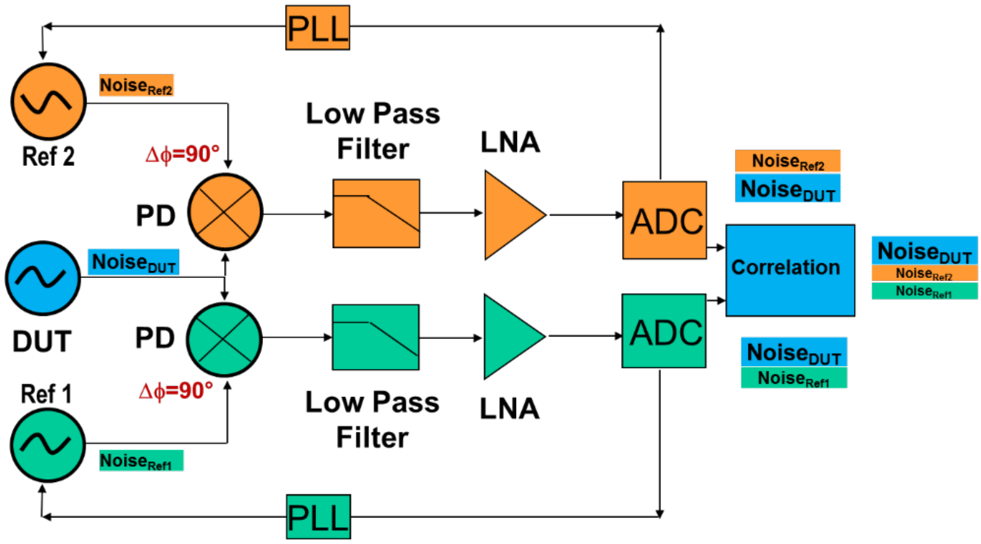


Fig. 2-8: Phase detector with cross correlation block diagram.

Figure 2-9 shows the result of a screenshot from an analyzer that uses cross-correlation. The DUT results are from the same oscillator as the one without cross-correlation (Figure 2-7). That measurement was about -132 dBc/Hz. With the same oscillator using cross-correlation, the result is -140, that's an 8 dB improvement in this example. Note that the measurement sensitivity improved by 20 dB, which resulted in a more accurate phase noise measurement showing an 8 dB improvement. This improvement actually matches the spec for that particular signal source.

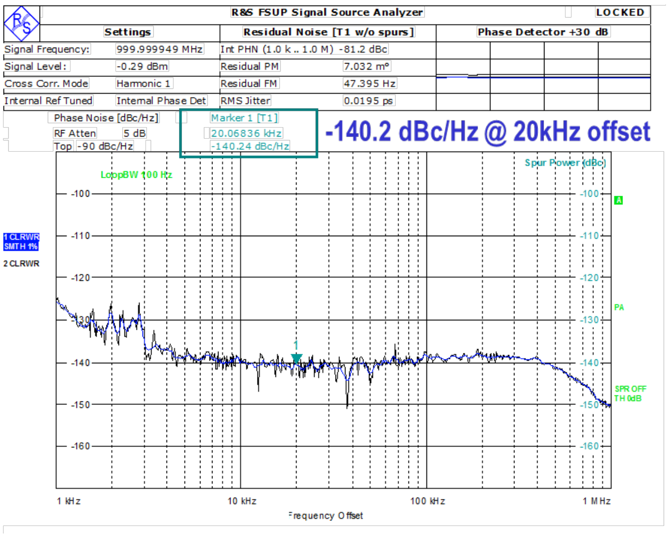


Fig. 2-9: Adding cross-correlation improves measurement sensitivity by 20 dB, resulting in a more accurate phase noise measurement.

3.4 Delay Line Discriminator

Another technique is the delay line discriminator, but it's not supported in Rohde & Schwarz equipment. This technique doesn't use a reference source, instead the DUT feeds into a power splitter, which goes to a long delay line on one side and a phase shifter on the other (Figure 2-10). The rest of the setup is similar to the other techniques.

The delay line converts frequency fluctuations to phase fluctuations, then the phase detector converts the phase fluctuations to voltage fluctuations. The phase shifter role is to achieve the 90 degree phase shift needed to maximize sensitivity.

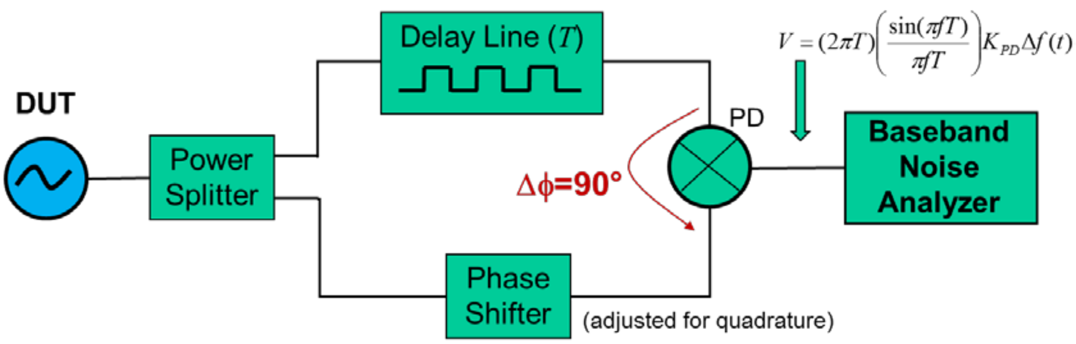


Fig. 2-10: Delay line discriminator block diagram.

This technique is good for noisy or drifting DUTs since no reference source is required. However, there's a reason that this isn't used that commonly and that is the delay line is going to have a lot of loss. This loss works against the sensitivity of the phase detector.

While the longer delay gives better sensitivity, it reduces the maximum usable frequency offset. In Figure 2-10 there is an equation in the upper right with a sin(x)/x term. This sin(x)/x term starts weighting the function down and, at high offsets, strange nulls in the phase noise curve appear (Figure 2-11). These aren't really a feature of the DUT, but a feature of the measurement technique. There is a limitation of this technique up to a frequency of 1/2π times the delay line length.

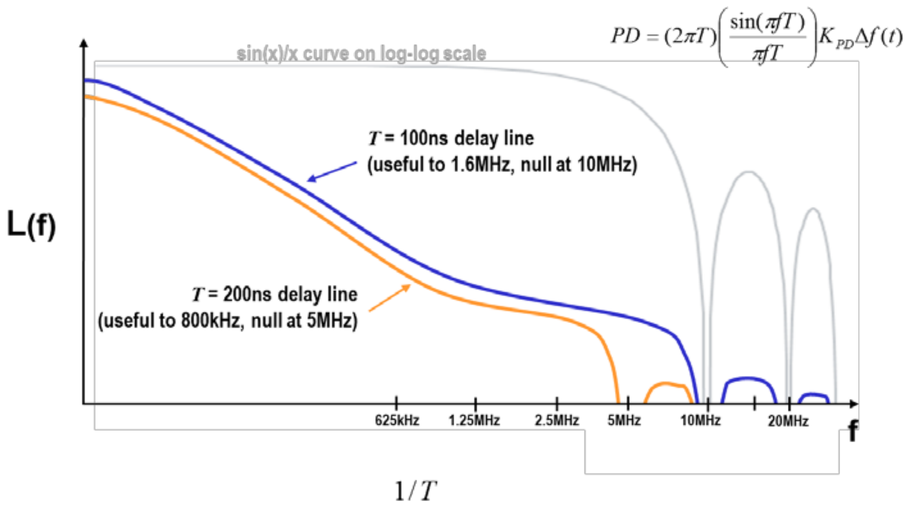


Fig. 2-11: The longer delay gives better sensitivity, but reduces the maximum usable frequency offset.

3.5 Digital Phase Demodulator

Rohde and Schwarz have introduced a new technique for measuring phase noise that is called the digital phase demodulator technique. Figure 2-12 shows a very simplified block diagram of our FSWP Phase Noise Analyzer. The DUT interface is similar to the spectrum analyzer setup and it accepts inputs from 1 MHz up to 50 GHz. The incoming DUT signal is spilt into two IQ mixers channels. We still use low pass filters and LNAs, but then the signal flows into a digitizer. This is where some really low-noise, high-speed hardware does a very high sensitivity, digital frequency demodulation, which is then converted to phase demodulation, and finally converted to phase noise.

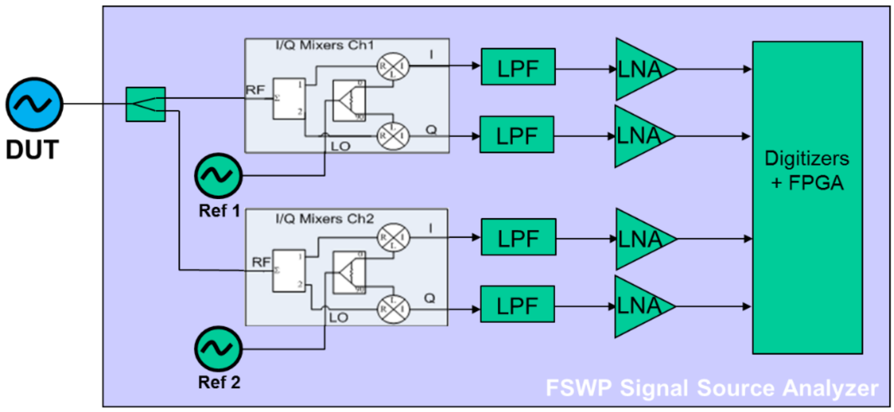


Fig. 2-12: Digital phase demodulator block diagram.

One advantage of this technique is that it does not use a phase detector. Therefore, it does not require a phase lock loop and the associated loop bandwidth correction, which greatly simplifies calibration and speeds up the overall measurement time.

In addition, our design uses very low-noise reference sources and very high-speed cross-correlation, which delivers state-of-the-art sensitivity. As a result, we can measure the phase noise on a low-level signal in the presence of a larger one. That's difficult to do with a phase detector. In section 3 we'll discuss new advantages when measuring additive, pulsed, and AM noise.

This digital phase demodulator technique offers a measurement speed improvement of more than 10x over traditional techniques. Figure 2-13 shows a very sensitive measurement of a 100 MHz crystal oscillator, which took less than 30 seconds. At a 10kHz offset we are measuring -174 dBc/Hz! This same measurement on a currently available phase detector cross-correlation system would take 10 minutes or more to get that level of sensitivity. It's a very fast and sensitive technique, with offsets available from 0.01 Hz out to 300 MHz.

One unique feature of the FSWP can be seen in the gray area below the phase noise curve. What this shows is the measurement margin. The user can adjust the amount of cross-correlation necessary to assure the needed signal-to-noise ratio for accurate results. This reduces the need to look up the specs of this analyzer.

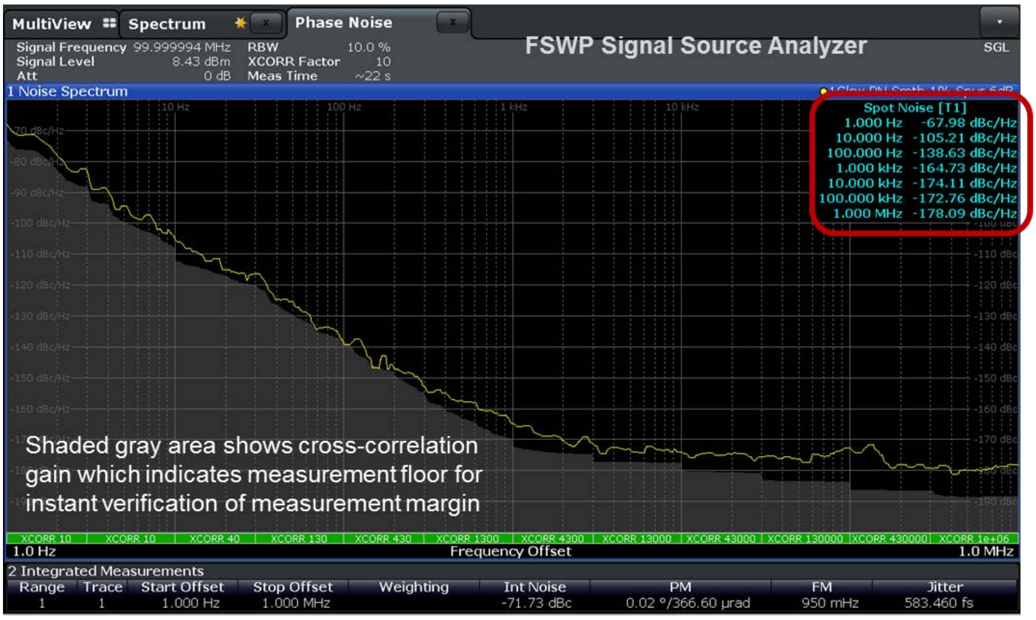


Fig. 2-13: Along with improved sensitivity the digital phase demodulator technique offers a measurement speed improvement of more than 10x over traditional techniques.

4 Summary

Minimizing phase noise is critical to achieving the performance required by many of today's RF applications. Part 1 of this series of application notes has covered the basics of phase noise, and in this Part 2 of the series, we looked at several traditional measurement techniques and introduced a new technique using the R&S FSWP. While the traditional techniques have been used for years, they are hindered by cumbersome calibration and often require additional hardware. Our new digital phase demodulation technique provides really low-noise reference sources and achieves fast correlations with simple setups that deliver state-of-the-art sensitivity and speed.

In Part 3 of this series, we will introduce some of the advanced phase noise measurements used to evaluate special device-under-tests (DUT) situations.

Please follow this link for more information on the R&S®FSWP Phase Noise Analyzer and VCO Tester.

- Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management ISO 9001

Certified Environmental Management ISO 14001

PAD-T-M: 3573.7380.02/02.05/EN/

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com

Mastering Phase Noise Measurements (Part 3)

Application Note

Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

Note: This application is part three of a three part series. See the end of this application note to view the first two parts.

Rohde & Schwarz
10.2016 – 01.03

ROHDE&SCHWARZ

Table of Contents

1 Introduction 3

2 Advanced Phase Noise Measurements 4

2.1 Additive Noise 4

2.1.1 Using the Digital Phase Demodulator Technique 4

2.2 Pulsed Measurements 5

2.2.1 Using the Digital Phase Demodulator Technique 7

2.3 AM Noise 9

2.3.1 Using the Digital Phase Demodulator Technique 9

2.4 Measurement Technique Summary 10

3 Summary 11

2 Introduction

Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications. Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

- Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- **Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise**

We will now cover part 3: Advanced Phase Noise Measurements

3 Advanced Phase Noise Measurements

Let's review some of the advanced phase noise measurements used to evaluate special device-under-tests (DUT) situations.

3.1 Additive Noise

The additive phase noise measurement technique measures the added noise of a device, such as an amplifier. The setup is a variation of the phase detector technique, with a power splitter in front of the DUT and a phase shifter added to the other path (Figure 2-1). The source noise is correlated on both sides of the phase detector inputs so that it cancels out, leaving only the added noise of the DUT to be measured. The phase shifter is used to maintain the 90 degree quadrature for maximum sensitivity, but it's also used in this measurement technique as a 180 degree calibration tool.

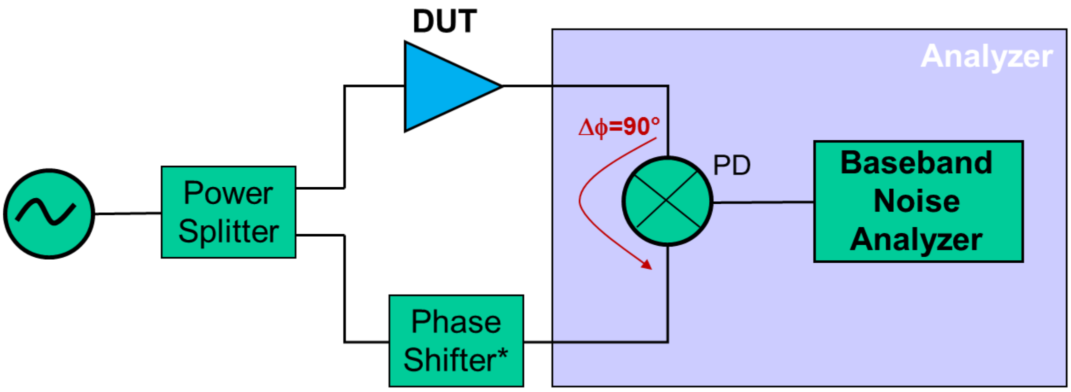


Fig. 2-1: Additive phase noise block diagram.

3.1.1 Using the Digital Phase Demodulator Technique

With the new FSWP digital phase demodulator additive phase noise measurements are as easy as pushing the "Additive phase noise" button. Internally, it re-plumbs itself to route the signal from one of the synthesizers out to the DUT plus some other changes internally (Figure 2-2). All of the measurement needs and setup are performed internally so the test engineer doesn't have to worry about calibration or phase shifters.

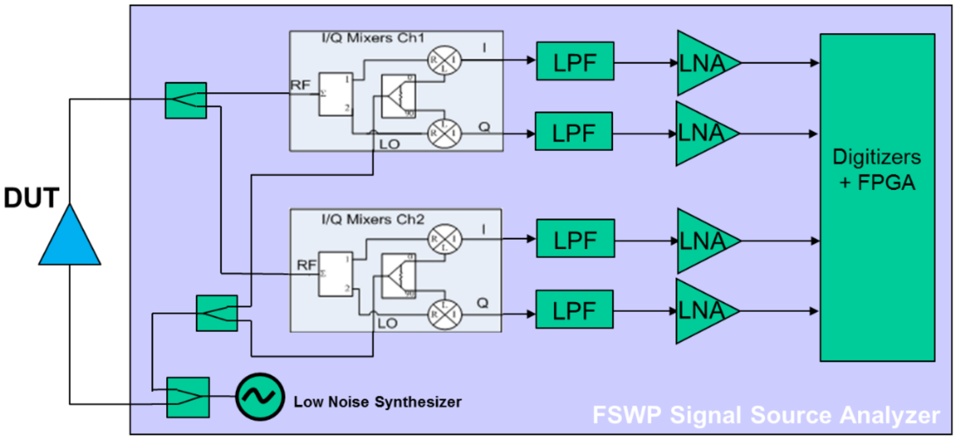


Fig. 2-2: Digital phase demodulator technique block diagram.

The additive phase noise measurement result is basically the same as a regular phase noise measurement, with the familiar curve, spot noise result, and also the gray area showing measurement margin (Figure 2-3). One interesting thing to note in this measurement result is the jitter value in the lower right corner shows 834 as or 834 attoseconds! After femtoseconds comes attoseconds, which is 10-15.

Fig. 2-3: Additive phase noise measured results.

3.2 Pulsed Measurements

With many applications requiring pulsed signals, the need for performing pulsed phase noise measurements is common. While the phase detector technique has been used for many years to perform these measurements, the pulsed signal adds a few twists.

When the pulse is on from the DUT, the phase detector will work properly with the CW reference signal. However, when the pulse is off from the DUT there would be a DC shift that throws off the phase lock loop.

To eliminate this DC shift during the off part of the burst, we have to synchronize the reference pulses with the pulses from the DUT (Figure 2-4). The pulse edges of the DUT and reference are not perfectly synchronized so switching transients will occur at pulse edges, resulting in pulse repetition frequency (PRF) feedthrough. The low pass filter (LPF) cutoff is too high to attenuate the PRF feedthrough. In order to make a sensitive phase noise measurement therefore requires a special PRF filter that is unique to a specific PRF of the DUT. A different PRF filter will be required for every PRF that needs to be measured.

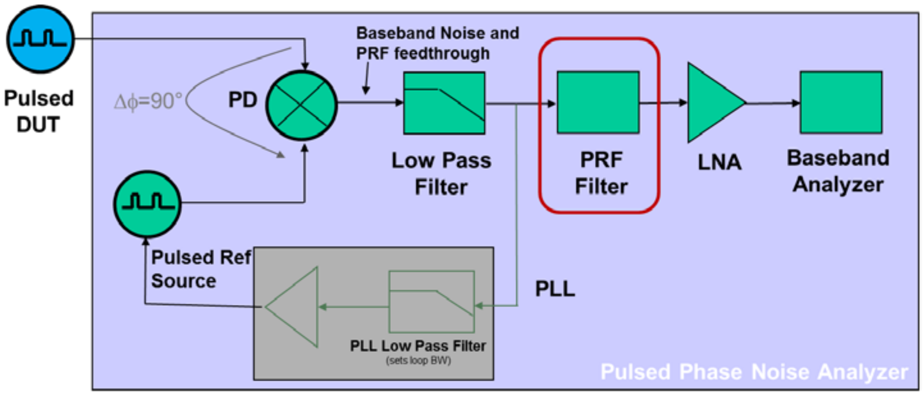


Fig. 2-4: Phase detector pulsed phase noise block diagram.

Since the PRF filter is a much narrower filter than the low-pass filter, it must a have flat passband with a sharp cutoff. Figure 2-5 shows spectrum of a pulsed CW signal that contains one line at the center frequency and many other PRF lines. The role of the PRF filter is to be narrow enough to pass the center line and attenuate all the other PRF lines.

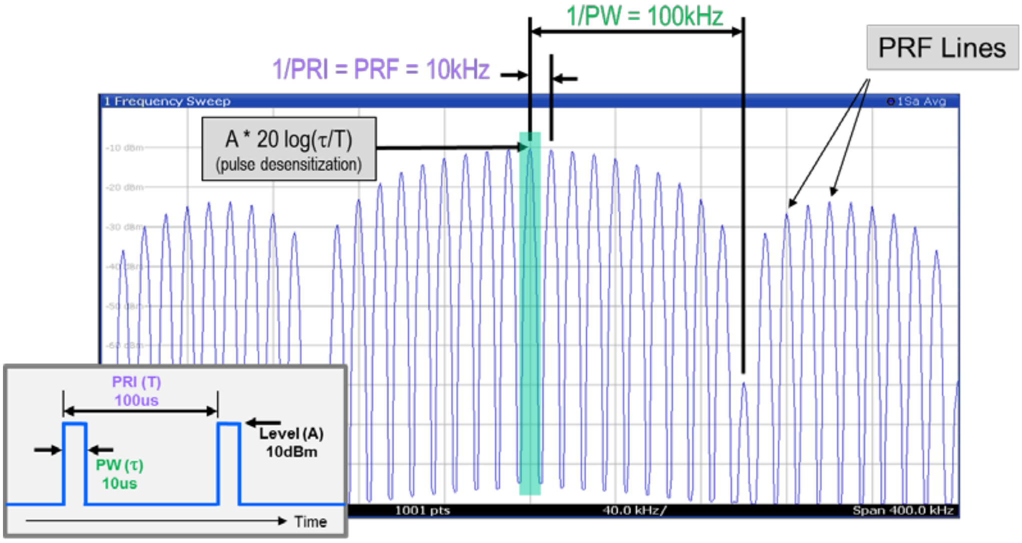


Fig. 2-5: The PRF filter is a much narrower filter than the low-pass filter and must a have flat passband with a sharp cutoff.

One problem is that the center line is lower than the pulse level due to pulse desensitization, by a factor of:

20*log(duty cycle)

In this example there is a 10% duty cycle, so the center line is 20 dB below the amplitude of the pulse. This reduces the sensitivity in the measurement. Building a PRF filter that achieves a flat passband, while having a high rejection of the PRF feed-through can be a challenge to design.

Figure 2-6 shows the example DUT’s phase noise in both pulsed and CW mode. The green line is the CW phase noise measured on a spectrum analyzer, the blue line is the pulsed phase noise result. Close in the phase noise matches closely as can be seen by their overlay.

As we approach the maximum offset, PRF/2 or 5 kHz here, the divergence starts. There is roughly 6 dB higher phase noise on the pulsed signal because of the coherent combining of the adjacent lines.

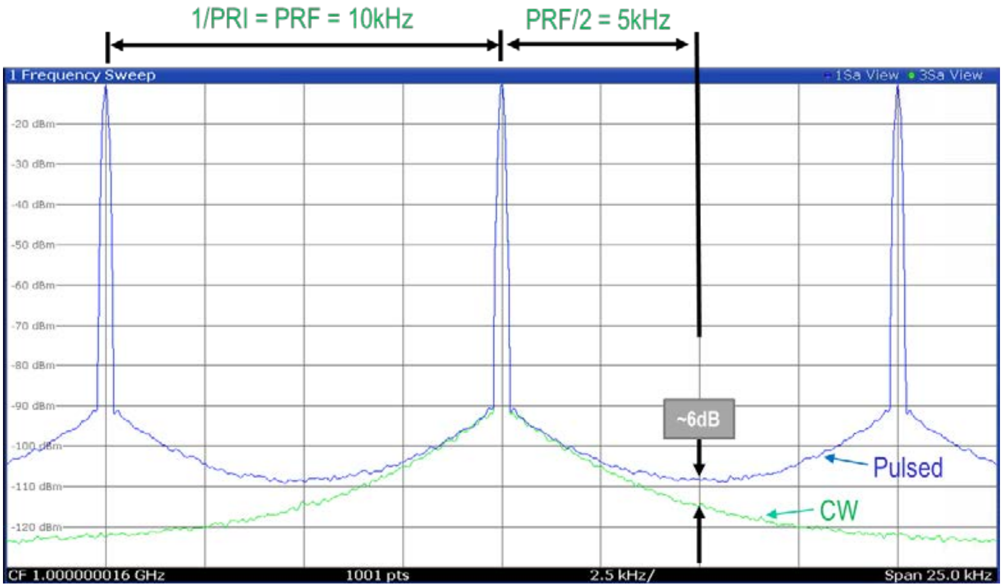


Fig. 2-6: Close in the phase noise matches closely, but divergence starts as the maximum offset of PRF/2 is approached

3.2.1 Using the Digital Phase Demodulator Technique

Now let's do the same pulse measurement using the digital phase modulator technique. The block diagram is going to be exactly the same as the CW measurement that was shown in Figure 2-2. Since there is not a diode-based mixer to be susceptible to the DC offset, the reference source does not have to be pulsed. The digitizer takes the incoming signal so there aren’t PRF glitches to worry about.

The analyzer does need to know something about the pulses so that it can set itself up internally in its DSP. Pushing the "Pulse configuration" button turns it into a spectrum analyzer. The pulse width (PW) and PRI are automatically detected using a zero-span measurement. The PW is used to set measurement gate time and the PRI is used to set maximum offset (Figure 2-7).

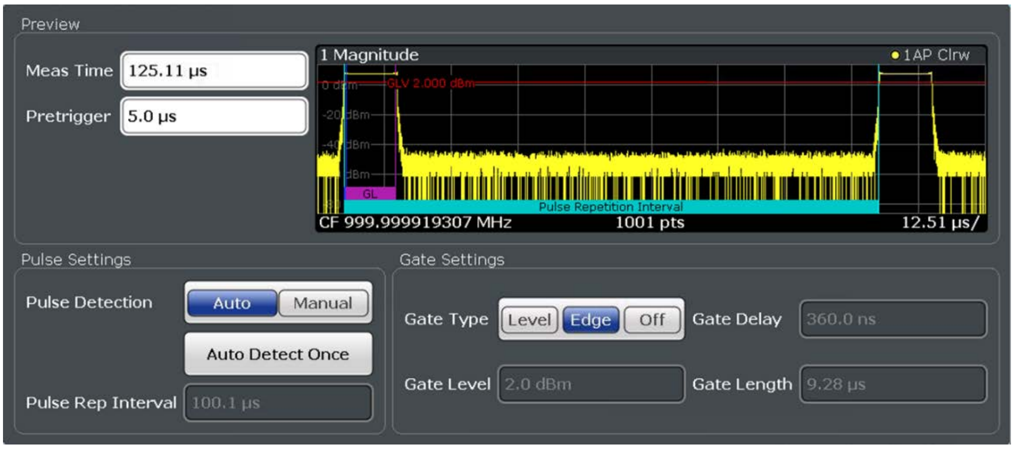


Fig. 2-7: Spectrum analyzer features are used to automatically setup for the pulse configuration

For the measurement, the analyzer automatically truncates the max offset, which in this case is 5 kHz for the 10 kHz PRF. The measurement time is identical to the CW case, and the gray area again represents the measurement margin between the DUT and the analyzer noise floor. Figure 2-8 shows the two captures of the same DUT, both CW and pulsed.

As with the spectrum analyzer result shown before, the two are matched very closely at the close-in offsets, with the divergence starting out toward PRF/2. The pulsed result starts rising up due to that coherent combining again.

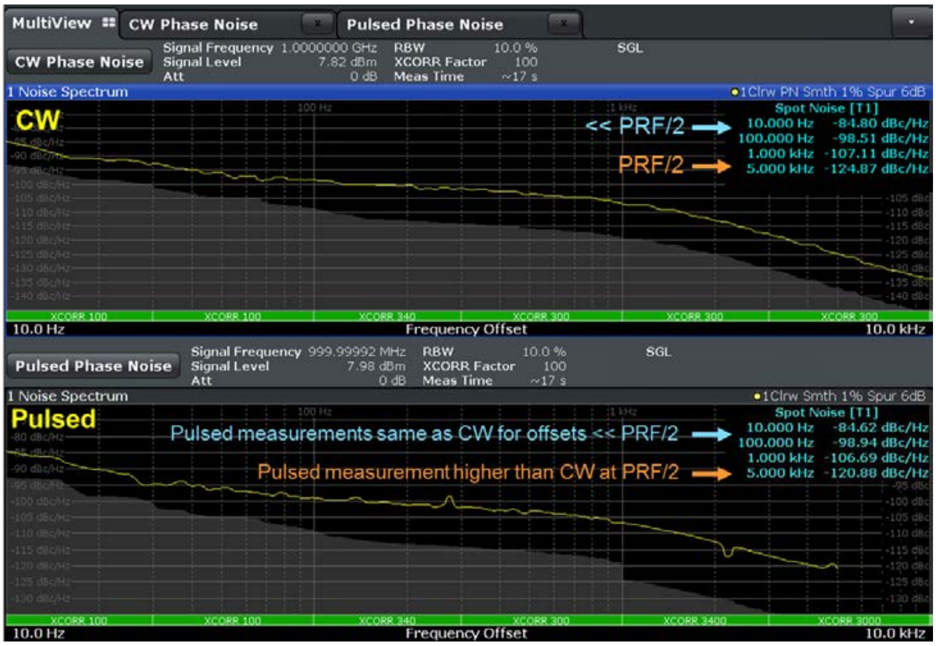


Fig. 2-8: Pulsed vs CW phase noise measurement results.

3.3 AM Noise

First let's recall the expression of our real-world sine wave:

$$V(t) = [A + E(t)] \sin(2\pi\nu t + \varphi(t)) \qquad (2)$$

where

$E(t) =$ amplitude fluctuations

$\varphi(t) =$ phase fluctuations

For most of this application note we have focused on the $\varphi(t)$ or phase noise. However, E(t) represents the AM noise component. AM noise is usually lower than phase noise, especially at close-in offsets. Traditional AM Noise is measured using an external diode detector along with the baseband noise analyzer (Figure 2-9). While the AM detector is insensitive to phase fluctuations and frequency, it is very sensitive to amplitude. Calibration of the measurement is done using a signal generator with a known AM modulation index.

These measurements are of low-level noise, which is very susceptible to external interference. This is a difficult setup to get good measurements. It requires the use of very well-shielded cables, preferably the whole test should be in a shielded room. Any amplitude noise that gets into that area between the AM detector and the noise analyzer will corrupt the measurement.

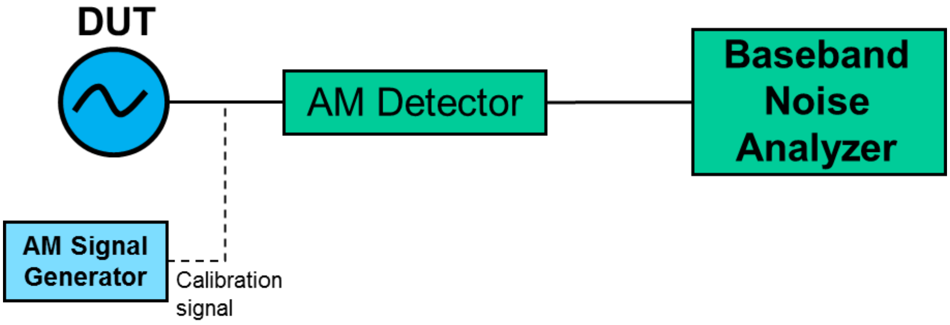


Fig. 2-9: AM detector phase noise block diagram

3.3.1 Using the Digital Phase Demodulator Technique

Once again the DUT just hooks directly up to the instrument as shown in Figure 2-2. Figure 2-10 shows the only thing that changes in the displayed results is down in the block on the right again, where all the calculations take place. Instead of doing FM and DM demodulation, the instrument is set to do AM demodulation. It's that simple. We don't have to worry about the detector diode or AM modulated source to calibrate.

One very unique aspect is that it can measure AM and phase noise simultaneously. Three measurement traces can be shown - the phase noise, the AM noise, and the total noise. Each of these can be overlayed. This technique provides an easy method for breaking out each of the phase noise components.

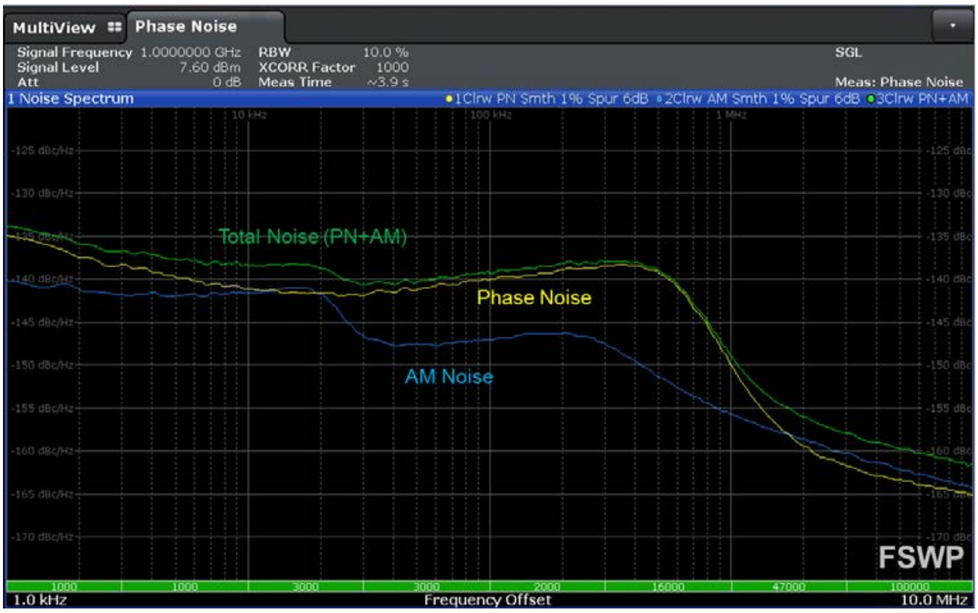


Fig. 2-10: Simultaneous measurement of AM noise and phase noise with total noise

3.4 Measurement Technique Summary

Table 2-1 summarizes each of the measurement technique's capabilities for the different types of measurements discussed – CW, additive, pulsed, and AM.

	CW	Additive	Pulsed	Pulsed-Additive	AM Noise
Direct SA	✓ Limited sensitivity and close-in offset	✗	✗	✗	✗
Phase Detector	✓	✓ Difficult cal required	✓ PRF filter required	✓ Difficult cal and PRF filter required	✓ Detector diode and AM cal source required
Delay Line Discriminator	✓ Max offset limited by sin(τ)/τ	✗	✗	✗	✗
Digital FM/AM Demodulator	✓	✓	✓	✓	✓

Table 2-1: Summary of measurement techniques.

4 Summary

Minimizing phase noise is critical to achieving the performance required by many of today's RF applications. Part 1 of this series of application notes has covered the basics of phase noise. Part 2 looked at several traditional measurement techniques and introduced a new technique using the R&S FSWP. And in this Part 3, we have covered some of the advanced phase noise measurements such as additive, pulsed and pulsed-additive measurements.
While the traditional measurement techniques for phase noise have been used for years, they are hindered by cumbersome calibration and often require additional hardware. Our new digital phase demodulation technique provides really low-noise reference sources and achieves fast correlations with simple setups that deliver state-of-the-art sensitivity and speed.

Please follow this link for more information on the R&S®FSWP Phase Noise Analyzer and VCO Tester.

- Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001

PAD-T-M: 3573.7380.02/02.05/EN/

01.03

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com